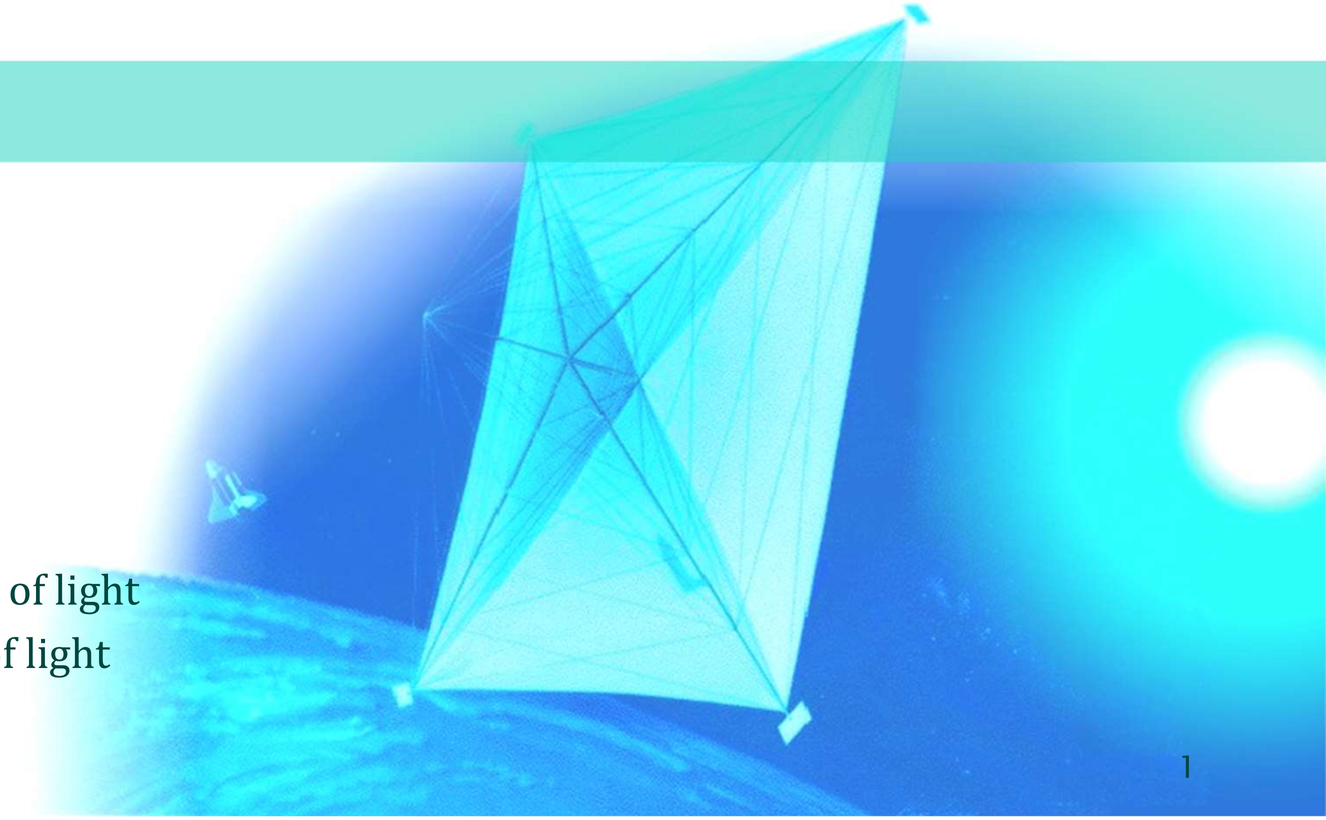
Photonics

Erwin Bente
Photonic Integration group
e.a.j.m.bente@tue.nl

Interaction of light with matter
devices for generation of light
detection of light



Schedule

Photons and Atoms	8, 10	Thursday	19-Sept
Photon and Atoms, Lasers	10, 13	Tuesday	24-Sept
Lasers	13	Thursday	26-Sept
Semiconductor light sources	14	Tuesday	8-Oct
Semiconductor light sources	14	Thursday	10-Oct
1 hour Test (Ch 8-13) Semiconductor detectors	15	Tuesday	15-Oct
Technology, Displays, Guest lecture	16,18	Thursday	17-Oct
Lab tours – Problems, Homework discussion, Q&A Erwin Bente		Tuesday	22-Oct
Lab tours – Problems, Homework discussion, Q&A Erwin Bente		Thursday	24-Oct

HW1

HW2

e.a.j.m.bente@tue.nl

Please check Canvas page on Schedule for more details

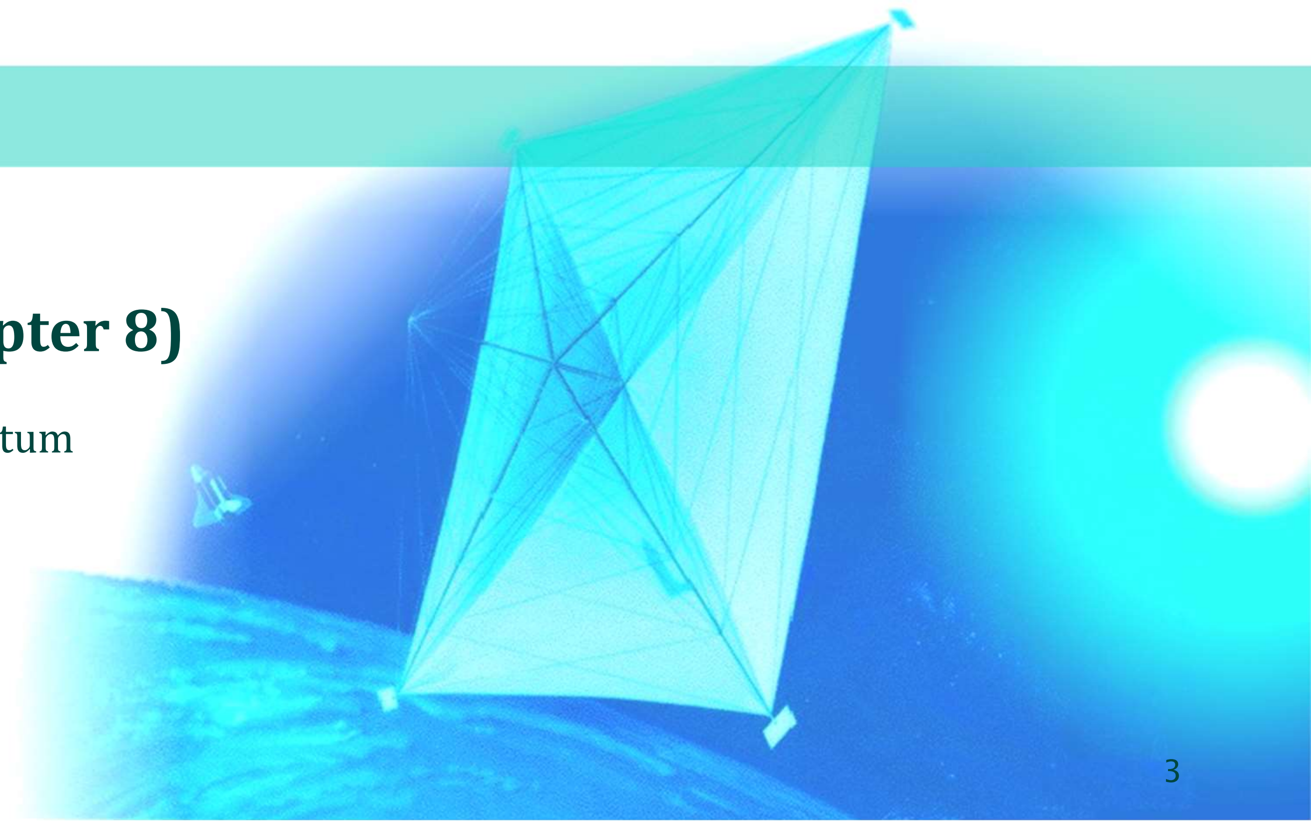
Photonics

Photon Optics (Chapter 8)

Photons, photon energy, momentum

Radiation pressure

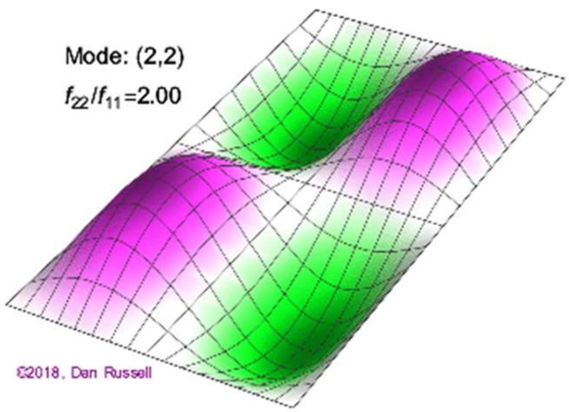
Photon stream, coherent light

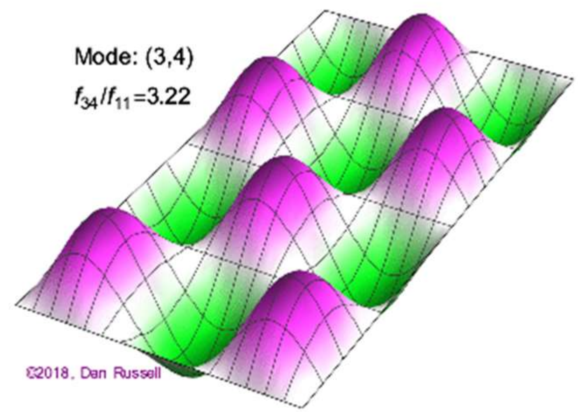


Electromagnetic radiation - normal modes

A superposition of normal modes of EM radiation describes field pattern propagating waves.
EM modes analogous to normal modes of vibration in other systems

Mode shapes for a Rectangular Membrane (2 dimensions) with $L_x = 2L_y$





Standing wave = sum of two counterpropagating travelling waves

all parts of the system move sinusoidally: same frequency - fixed phase relation

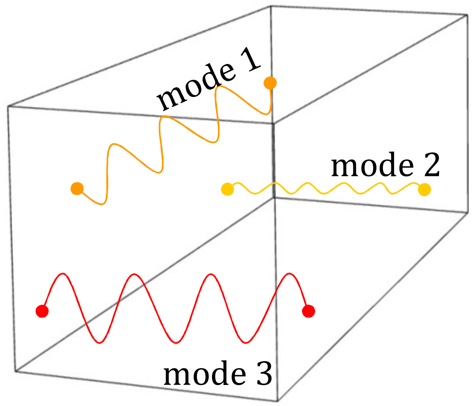
Figures from: https://www.acs.psu.edu/drussell/Demos/rect-membrane/rect-mem.html

Photons

Electromagnetic radiation or field mode

You can think of:

standing **plane waves** in a large **cavity**
with perfectly conducting walls



The mode density per **unit volume** per **unit frequency** turns out to be independent of size and shape of the cavity

mode density: $$M(\nu)d\nu = \frac{8\pi\nu^2}{c^3}d\nu$$

This value is also valid for free space!

Photon energy

The energy in the mode with frequency ν can change only in discrete steps.
It is quantized in what are called photons.

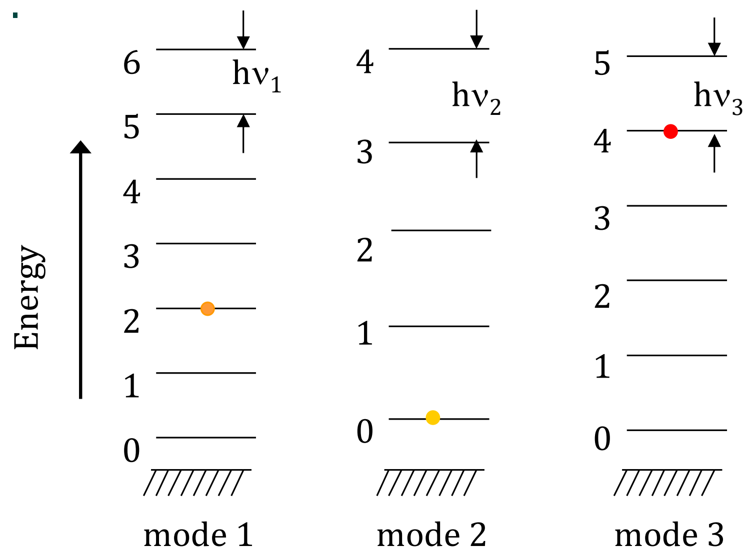
- Photon energy $\boxed{E = h\nu}$ h = 6.626 10^{-34} Js Planck's constant

- Energy of the EM mode $E_n = (n + 1/2)\, h\nu$, n=0, 1, 2, . . .

Zero point energy

Energy change in EM mode:

absorption or generation of photons by matter.
(atom, molecules, electrons etc.)

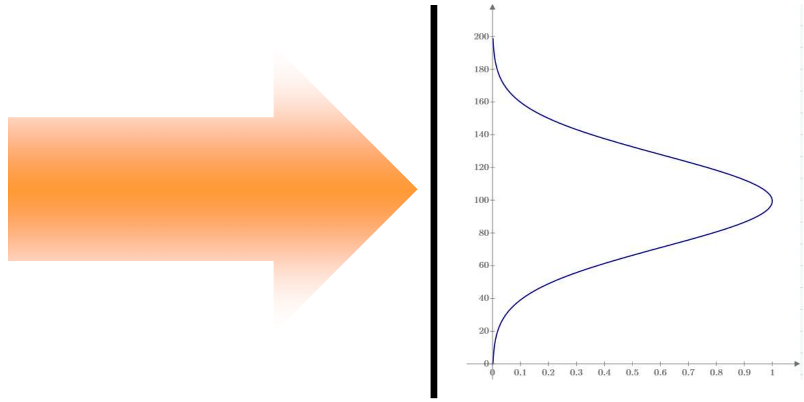


Example 8.1

The photon

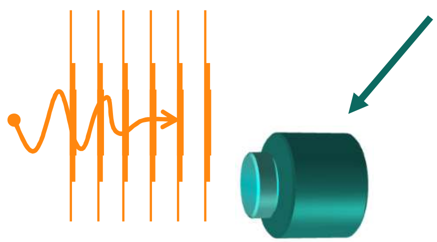
- Measuring the position of a photon

Light beam



Intensity distribution across the beam

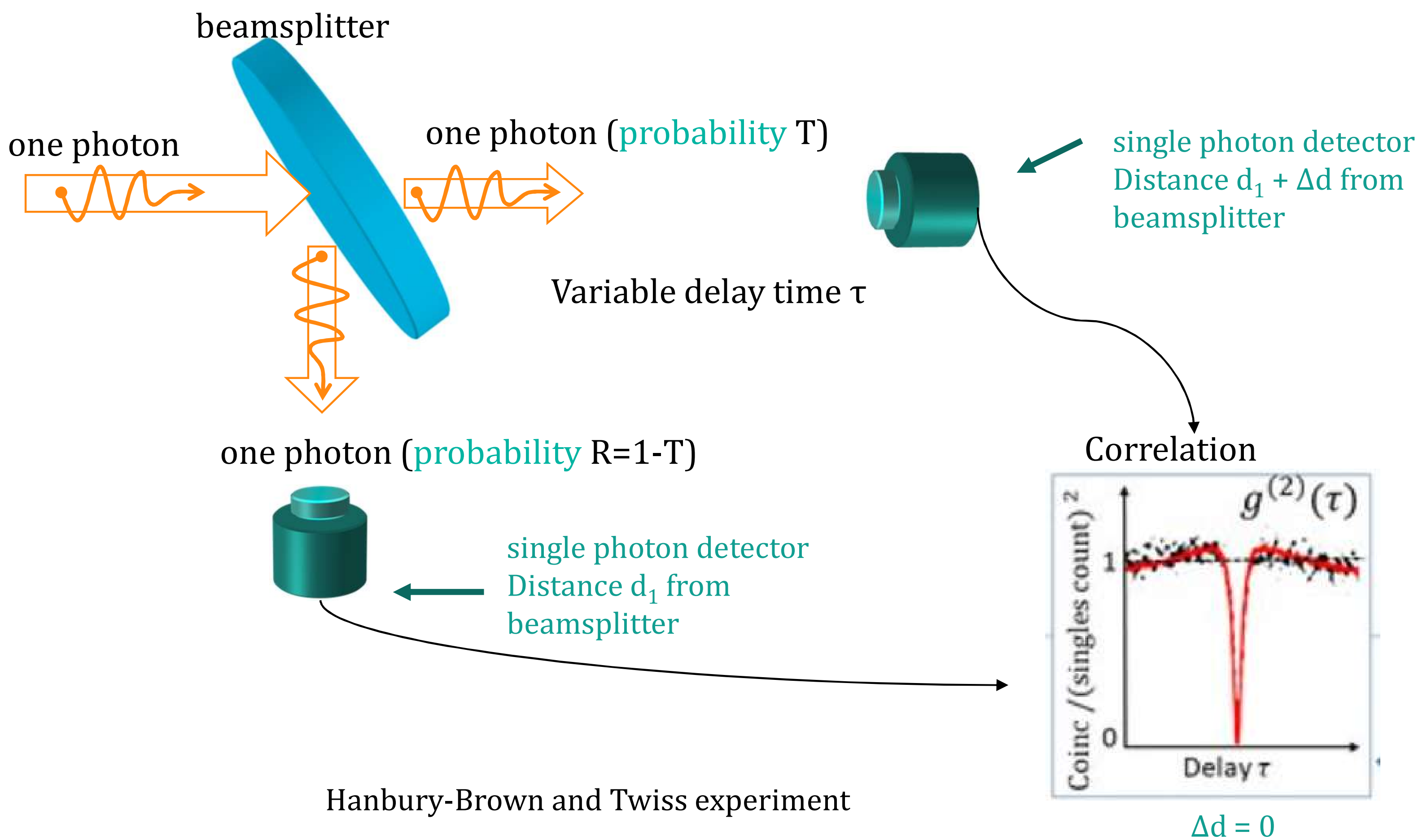
A single photon in the beam



single photon detector (see Chapt. 15) will detect a photon or not

will detect the photon with a probability proportional to local intensity of the wave at the detector

Where does the photon go?



Hanbury-Brown and Twiss experiment

Momentum of a photon

A photon carries momentum $\boxed{\vec{p} = \hbar \vec{k}}$ $\hbar = \dfrac{h}{2\pi}$

The momentum is a vector proportional to the k vector (see chapter 4).

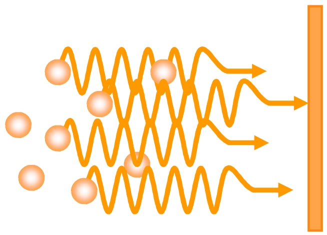
The magnitude of the momentum $\left|\vec{p}\right| = \hbar\left|\vec{k}\right| = \dfrac{h}{\lambda} = \dfrac{h\nu}{c} = \dfrac{E}{c}$

The relation follows from the theory of relativity

Momentum is a property that is associated with particles.

Radiation pressure

When N photons/s are absorbed their momentum is transferred



Radiation pressure

$$P = \frac{dp}{dt} = N\frac{h}{\lambda}$$

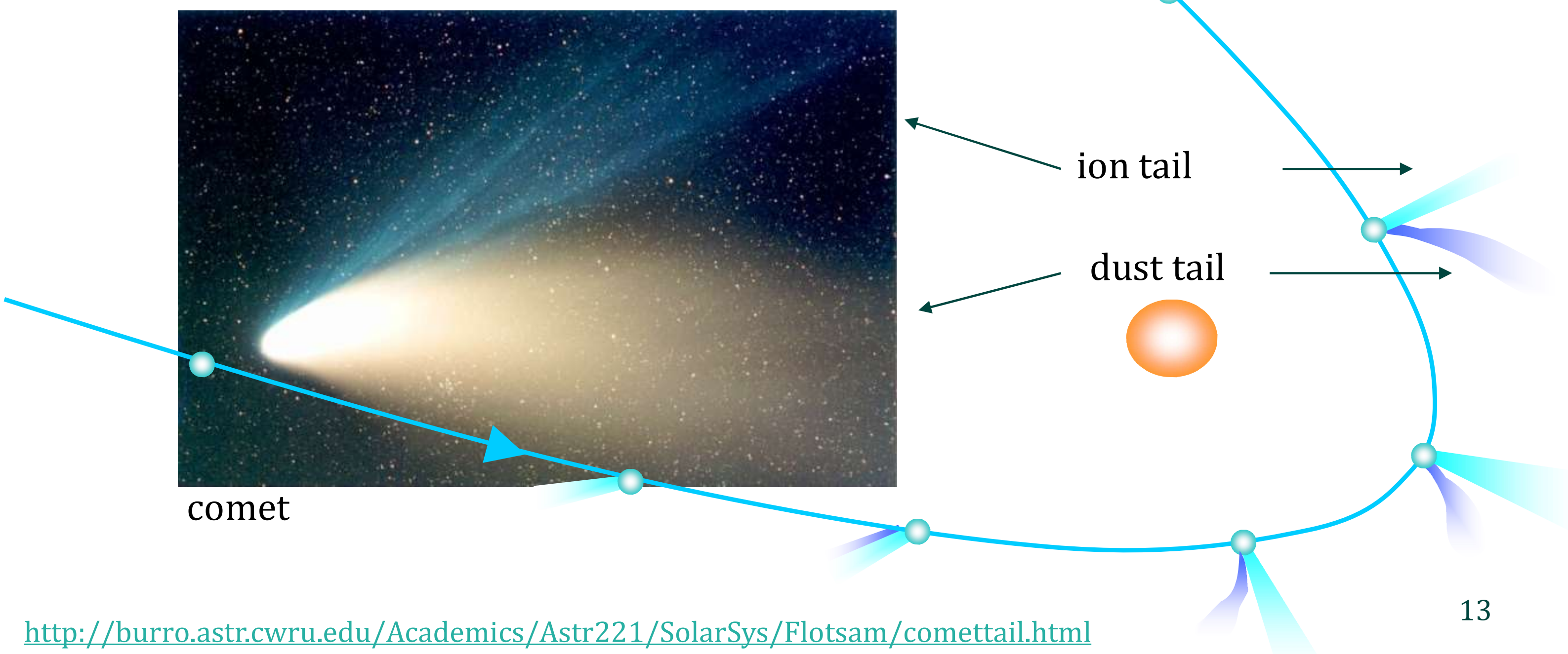
Application:

- Affects course of interplanetary space craft.
  - (e.g. 15000 km difference for Viking spacecraft to Mars, Eugene Hecht, "Optics", 4th edition)
  - The Pioneer anomaly (https://en.wikipedia.org/wiki/Pioneer_anomaly)
- Solar sail:
  - IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun, http://global.jaxa.jp/projects/sat/ikaros/topics.html#topics4743, https://en.wikipedia.org/wiki/IKAROS)
  - Interstellar travel proposal http://physicstoday.scitation.org/do/10.1063/PT.5.2035/full/
- Trapping and cooling atoms for quantum computing

Example 8.2

Radiation pressure (2)

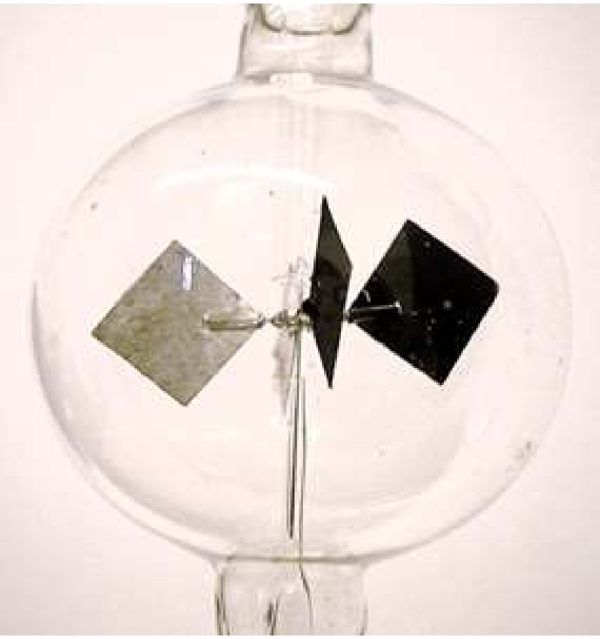
- Comet has typically two tails
  - dust particles: smaller particles absorb and reflect sunlight and are affected by radiation pressure (r<~0.006 cm) and solar wind (particles)
    the reflected light looks white, smallest particles are affected by solar wind (particles)
  - ions: mostly CO^+, N_2^+, CO_2^+ interact with solar wind and magnetic field lines (the blue light is mainly CO_2^+)



http://burro.astr.cwru.edu/Academics/Astr221/SolarSys/Flotsam/comettail.html

This does not work on radiation pressure

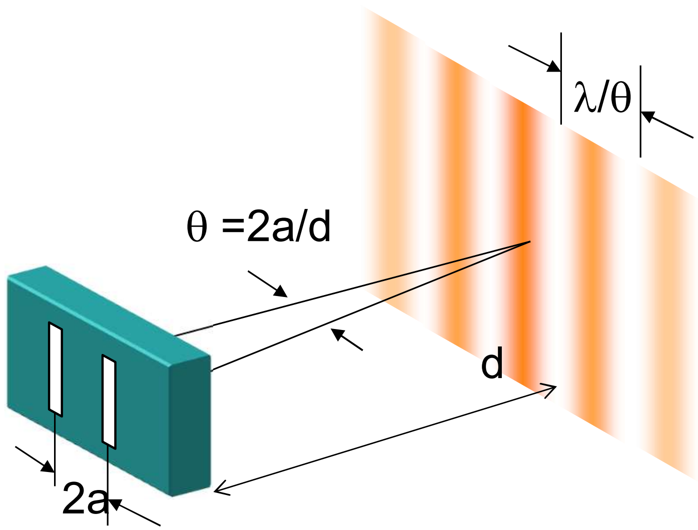
Crookes radiometer

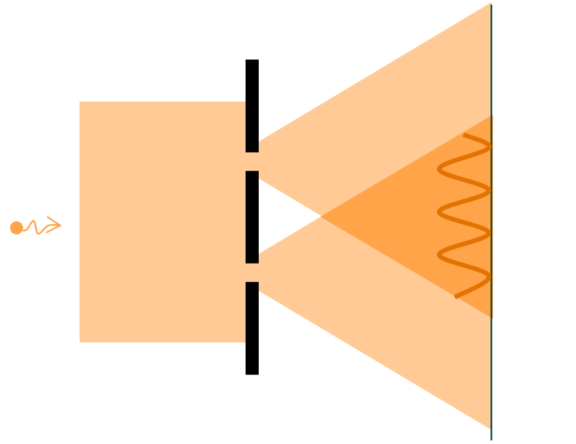


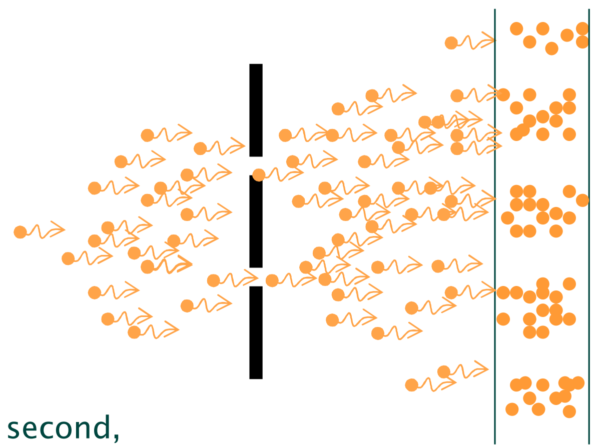
https://en.wikipedia.org/wiki/Crookes_radiometer

Photon – wave particle duality

- Photon interference (chapter 4.5)







Even when the light source produces only one photon a second,
you still have the interference pattern appearing (after waiting a long time)
https://youtu.be/GzbKb59my3U

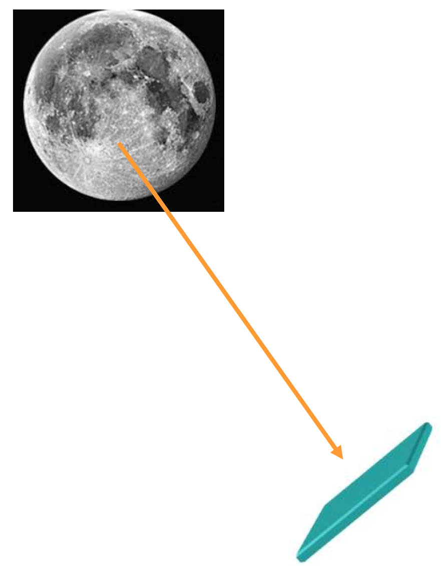
Photon streams

- Average photon flux
  - Power density [W/m²]

    $\Downarrow$

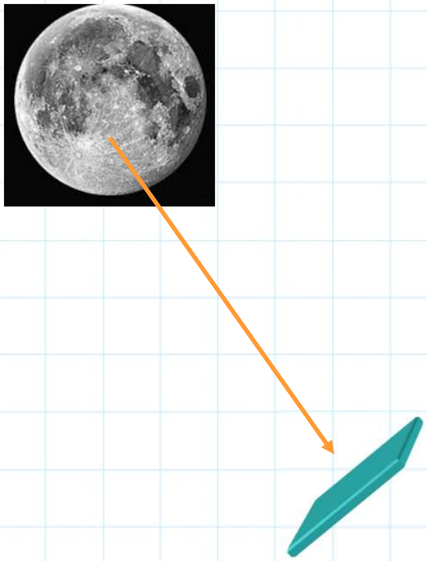
    average photon flux density [photons/s•m²]

$$\boxed{\begin{array}{l}\text{When } \lambda = 200\text{nm (UV)} \\ 1\ \text{nW} = 1\ \text{photon}\ /\text{ns}\end{array}}$$



Example 8.3

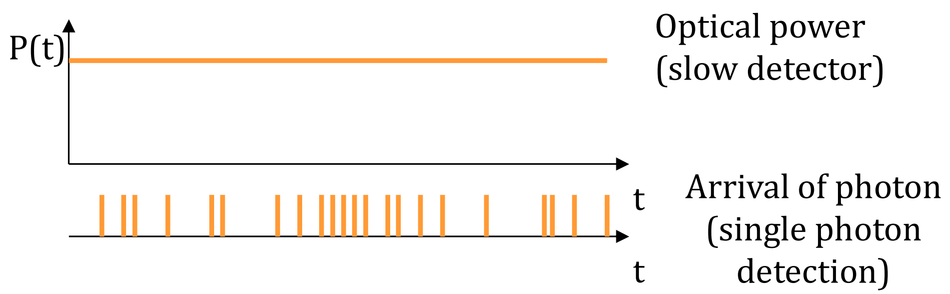
Full moon ± 0.25 lux

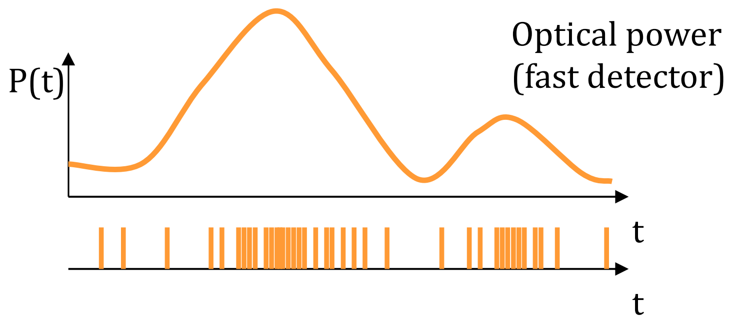


Photon stream

- Statistics of the photon flux

coherent light ⇔ thermal light





Photon stream – single mode

- Coherent Light (e.g. laser light)
  - Probability $p(n)$ of n photons arriving in time interval ΔT

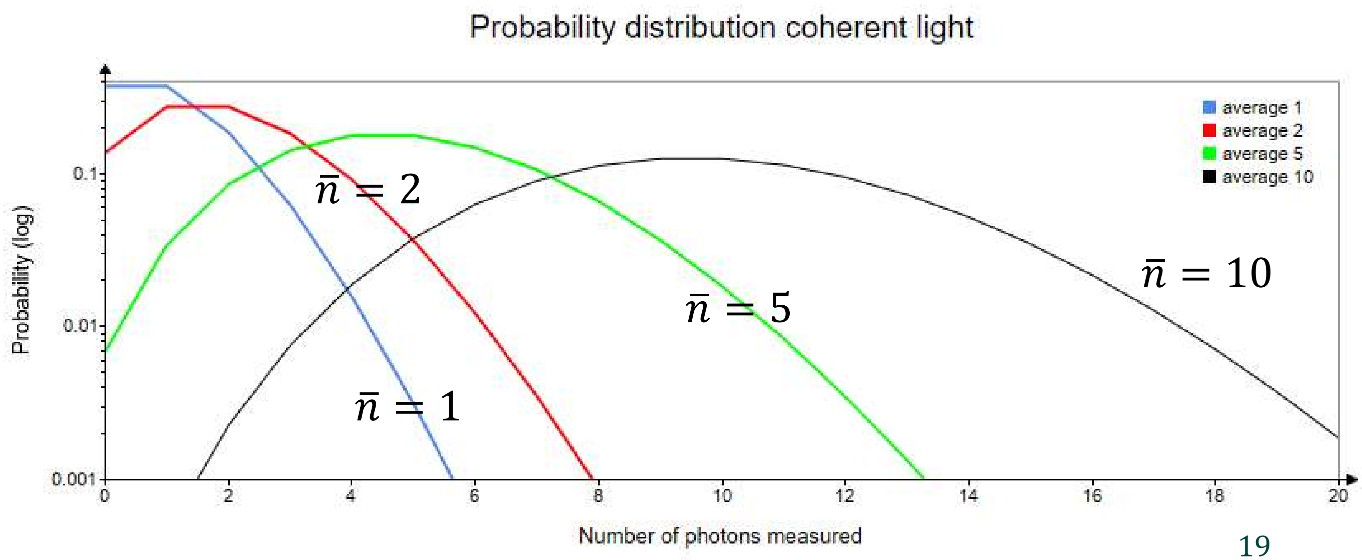
$$p(n) = \frac{\bar{n}^n e^{-\bar{n}}}{n!}$$

(Poisson distribution) shot noise

  - average number of photons in ΔT: $\bar{n}$
  - Variance : $\bar{n}$
  - standard deviation= $\sqrt{\bar{n}}$

"noise" becomes smaller for a larger number of photons (more power)

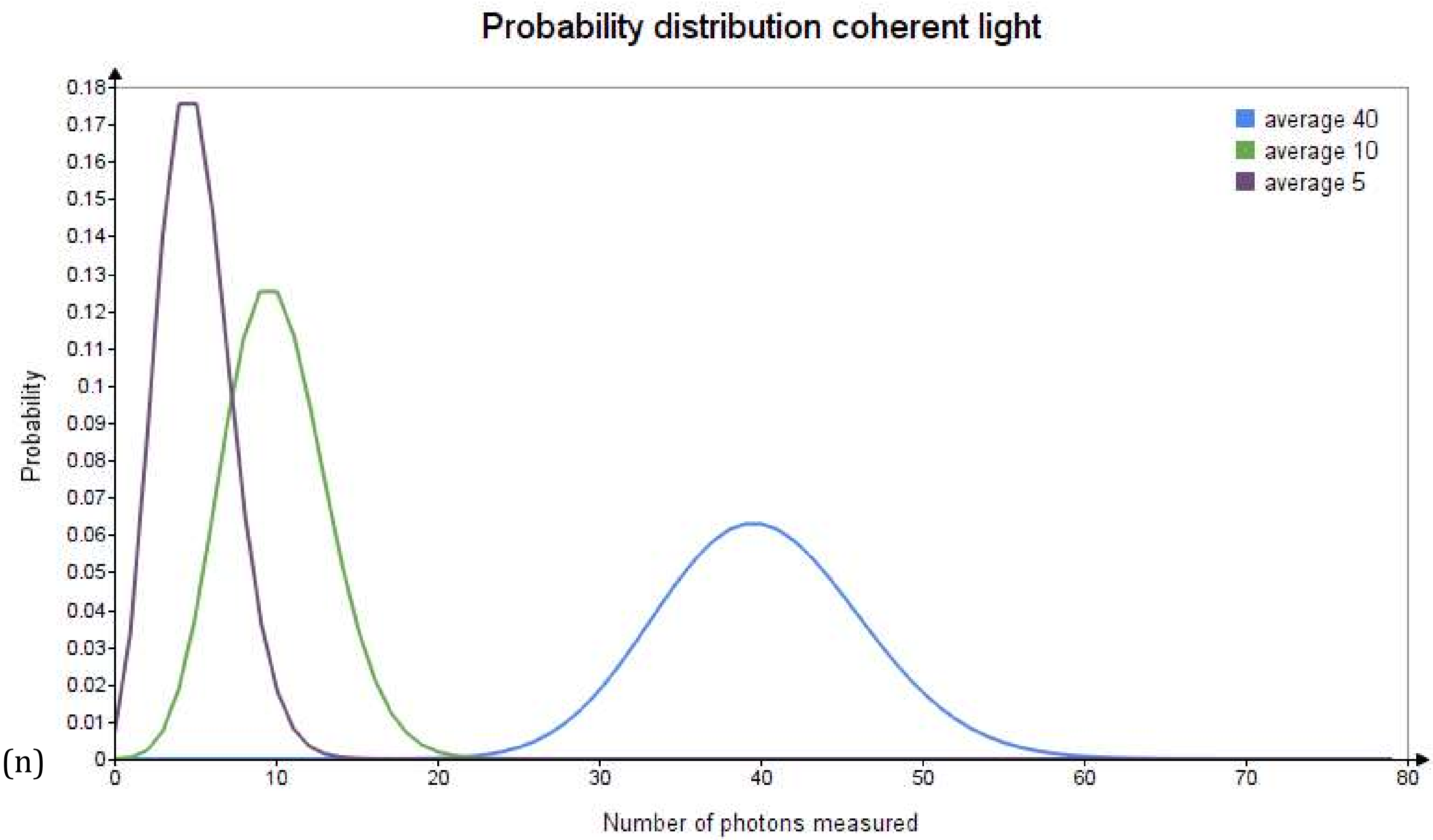
$p(n)$



Note log scale P(n)

Example 8.4

Photon stream – single mode



Linear scale P(n)

Example 8.4

Review questions

- What is a photon? Discuss it's basic properties.
- What is meant by the particle-wave duality?
- What determines intensity noise in an electromagnetic radiation beam?
- How does splitting a light beam affect its intensity noise?